Ocean Surface Wave Optical Roughness – Innovative Measurement and Modeling

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LONG-TERM GOALS

We are part of a multi-institutional research team funded by the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) program. The primary research goals of the program are to (1) examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes; (2) construct a radiance-based SBL model; (3) validate the model with field observations; and (4) investigate the feasibility of inverting the model to yield SBL conditions. Our goals are to contribute innovative measurements, analyses and models of the sea surface roughness at length scales as small as a millimeter. This characterization includes microscale and whitecap breaking waves.

The members of the research team are:

Michael Banner, School of Mathematics, UNSW, Sydney, Australia

Johannes Gemmrich, Physics and Astronomy, UVic, Victoria, Canada

Russel Morison, School of Mathematics, UNSW, Sydney, Australia

Howard Schultz, University of Massachusetts, Dept. Computer Science, Amherst MA

Christopher Zappa, Lamont Doherty Earth Observatory, Palisades, NY

OBJECTIVES

Nonlinear interfacial roughness elements - sharp crested waves, breaking waves as well as the foam, subsurface bubbles and spray they produce, contribute substantially to the distortion of the optical transmission through the air-sea interface. These common surface roughness features occur on a wide range of length scales, from the dominant sea state down to capillary waves. Wave breaking signatures range from large whitecaps with their residual passive foam, down to the ubiquitous centimeter scale microscale breakers that do not entrain air. There is substantial complexity in the local wind-driven sea surface roughness microstructure, including very steep nonlinear wavelets and breakers. Traditional descriptors of sea surface roughness are scale-integrated statistical properties, such as significant wave height, mean squared slope (e.g. Cox and Munk, 1954) and breaking probability (e.g. Holthuijsen and

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Herbers, 1986). Subsequently, spectral characterizations of wave height, slope and curvature have been measured, providing a scale resolution into Fourier modes for these geometrical sea roughness parameters. More recently, measurements of whitecap crest length spectral density (e.g. Phillips et al, 2001, Gemmrich et al., 2008) and microscale breaker crest length spectral density (e.g. Jessup and Phadnis, 2005) have been reported.

Our effort seeks to provide a more comprehensive description of the physical and optical roughness of the sea surface. We will achieve this through the analysis of our suite of comprehensive sea surface roughness observational measurements within the RADYO field program. These measurements are designed to provide optimal coverage of fundamental optical distortion processes associated with the air-sea interface. In our data analysis, and complementary collaborative effort with RaDyO modelers, we are investigating both spectral and phase-resolved perspectives. These will allow refining the representation of surface wave distortion in present air-sea interfacial optical transmission models.

APPROACH

We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team (listed above) measuring and characterizing the surface roughness. This team is contributing the following components to the primary sea surface roughness data gathering effort in RaDyO:

- *polarization camera measurements* of the sea surface slope topography, down to capillary wave scales, of an approximately 1m x 1m patch of the sea surface (see Figure 1), captured at video rates. [Schultz, Zappa]
- *co-located and synchronous orthogonal 75 Hz linear scanning laser altimeter* data to provide spatio-temporal properties of the wave height field (resolved to O(0.5m) wavelengths) [Banner, Morison]
- *high resolution video imagery* to record whitecap data from two cameras, close range and broad field [Gemmrich]
- *fast response, infrared imagery* to quantify properties of the microscale breakers, and surface layer kinematics and vorticity [Zappa]
- *air-sea flux package including sonic anemometer* to characterize the near-surface wind speed and wind stress [Zappa]

The team's envisaged data analysis effort includes: detailed analyses of the slope field topography, including mean square slope, skewness and kurtosis; laser altimeter wave height and large scale wave slope data; statistical distributions of whitecap crest length density in different scale bands of propagation speed and similarly for the microscale breakers, as functions of the wind speed/stress and the underlying dominant sea state. Our contributions to the modeling effort will focus on using RaDyO data to refine the sea surface roughness transfer function. This includes the representation of nonlinearity and breaking surface wave effects including bubbles, passive foam, active whitecap cover and spray, as well as micro-breakers.

WORK COMPLETED

My effort in FY10 has comprised: (i) a collaborative analysis of the sea surface roughness measurements gathered with the polarimeter during the RaDyO field experiments in the Santa Barbara

channel during September 5-27, 2008 and Hawaii during August 23-September 16, 2009; (ii) collaborative validation of the scanning lidar data from each of the 2008 field experiments from the scanning lidars, configured to operate in quadrature, deployed on FLIP to measure the large scale wave geometry (height and slope components). These measurements were collocated with the polarimeter, infrared and optical imaging systems collecting the surface roughness data.

In addition, an algorithm was developed that computes a height array by integrating the x and y-slope arrays. The inputs to the algorithm are the x and y-slope arrays derived from the imaging polarimeter data, the output is the surface elevations. Figure 1 shows a sample frame of the x and y slopes and the corresponding visualization of the surface heights. Video clips of the slope and height sequences can be downloaded using the following links:

http://vis-www.cs.umass.edu/~hschultz/WaveTank/2008_Run42_XandYSlopes_Cam4_Frames8891-10152_w_trailer-1.wmv
http://vis-www.cs.umass.edu/~hschultz/WaveTank/Z_movie.wmv

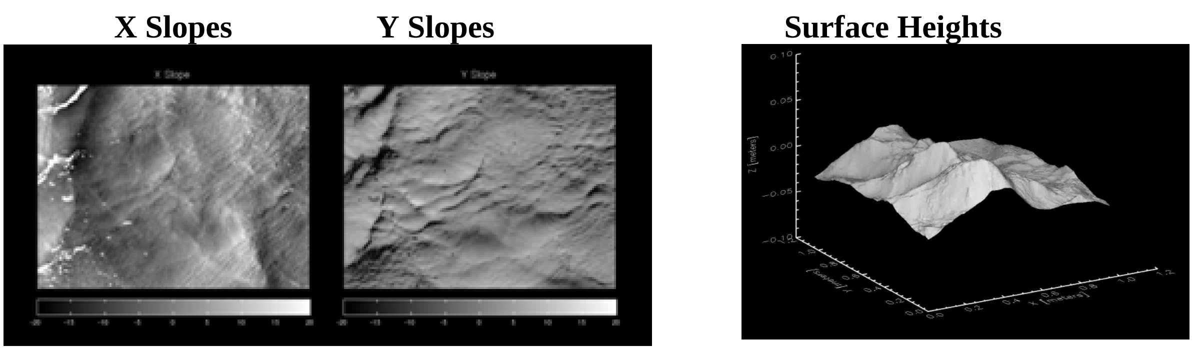


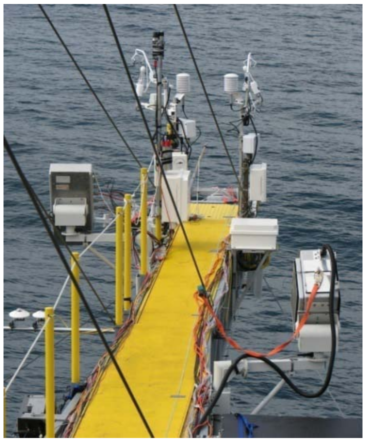
Figure 1. Imaging polarimeter results. (left) a sample frame of X and Y slopes; (right) a sample 3D visualization of the surface height made by integrating the X and Y slopes. The heights have a 6:1 vertical exaggeration.

RESULTS

Figure 2 below shows the instrumentation deployed in the field measurement phase. Schultz deployed an instrument package located on the boom that includes an imaging polarimeter for imaging small-scale waves. Zappa deployed his infrared/visible camera system and his environmental monitoring system (sonic anemometer, water vapor sensor, relative humidity/temperature probe, motion package, pyranometer and pyrgeometer). Gemmrich deployed 2 video visible imagery cameras. One camera was mounted on the main boom next to our other instrumentation packages, the second camera was mounted higher up to view larger scale breaking events.

Banner/Morison deployed two orthogonal line scanning lidars, positioned so that their intersection point was within the common footprint of the polarimetric (Schultz), infrared (Zappa) and visible (Gemmrich) imagery cameras, which were measuring small-scale surface roughness features and breaking waves. The individual data acquisition systems were synchronized to GPS accuracy which allowed the various data sets to be interrelated to within 0.1 seconds.

As can be seen in figure 1, the polarimetric camera appears to recover the slope and height of the very short waves that characterize the sea surface microstructure. The lidars characterizes the background wave environment. The simultaneous polarimetry and lidar data allows for an in situ validation of the polarimeter slope data.



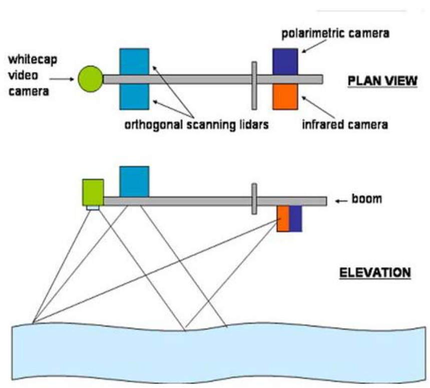


Figure 2. The left panel shows the instrumentation set-up deployed from the FLIP starboard boom. The right panel shows a schematic of instrumentation packages deployed. The end of the boom was about 8m above the mean water level. The approximate field of view of the various instruments is shown. A second wide angle whitecap video camera was mounted on FLIP well above the boom to image the larger whitecaps.

Figure 3 shows the close visual correspondence of the typical 1-meter baseline slope derived from the scanning lidar signal and co-located polarimeter.

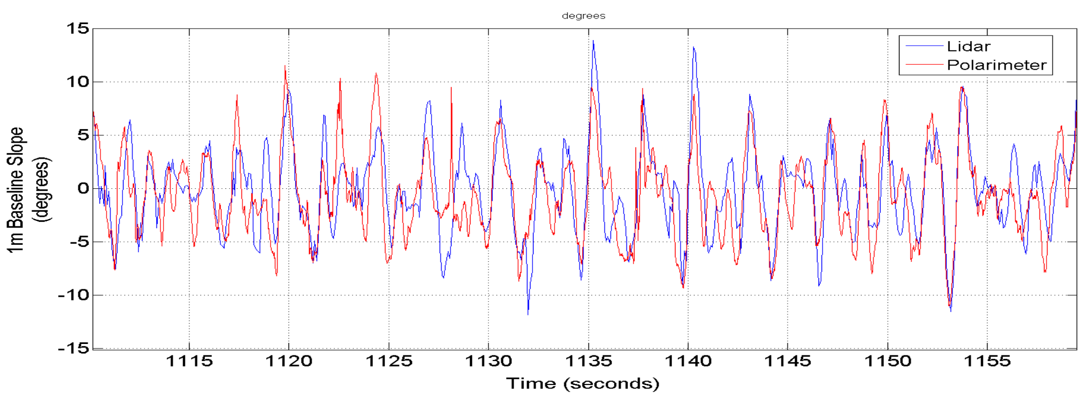


Figure 3. Comparison time series of the local wave slope over a 1 meter baseline determined from the polarimeter and scanning lidar instruments. These data were taken from FLIP in approximately 15 knot winds in the Santa Barbara channel during September, 2008.

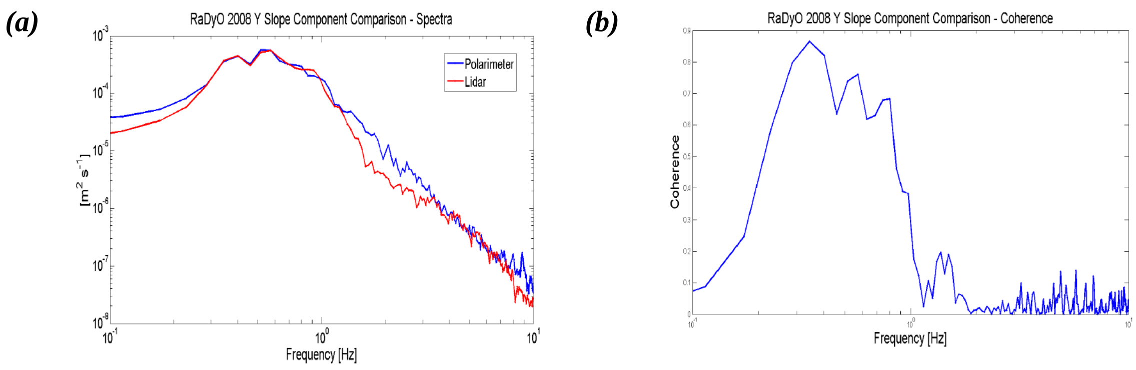


Figure 4. (a) frequency spectra of the 20 minute records containing the signals shown in Figure 3; (b) coherence between the slope data sets in Figure 3.

Figure 4a shows very close agreement for frequency spectra of 20 minute records containing the two 1-meter baseline slope signals shown in Figure 3. Figure 4b shows the coherency spectra between the lidar and polarimetric signals. Keeping in mind that the coherency spectra gives the correlation between two signals as a function of frequency, Figure 4b shows that the lidar and polarimeter results are highly correlated in the frequency range 0.3 to 1.0 Hz. In the coherent band [0.3-1.0Hz] it is reasonable to assume that the polarimeter and lidar validate each other. Outside the coherent band, however, we know only that the lidar and polarimeter disagree; it is not possible to determine which one, if any, are accurately recovering surface slopes.

It can be shown that the frequency domain integration scheme used to compute a height array from a pair of x and y slope arrays amplifies the low-frequency components of the noise. Whereas, the spatial domain differentiation scheme used to compute slopes from lidar range measurements amplifies the high-frequency noise. Therefore, it is reasonable to assume that the polarimeter provides better results for frequencies greater than 1.0 Hz and the lidar provides better results for frequencies less than 0.3 Hz. The comparison study between the imaging polarimeter and scanning lidar showed that the instruments complement each other—the polarimeter produces best results for high-frequencies, the lidar produces best results for low-frequencies (including the mean water level), and the two instruments cross-validate each other in the mid-frequencies.

IMPACT/APPLICATIONS

This effort will provide a far more detailed characterization of the wind driven air-sea interface, including wave breaking (whitecaps and microscale breaking). This is needed to provide more complete parameterizations of these processes, which will improve the accuracy of ocean optical radiative transfer models and trans-interfacial image reconstruction techniques.

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